Advances in Rover Technology for Space Exploration

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Session C3: Mars Technology (Moderator, Dave Lavery)

Overview

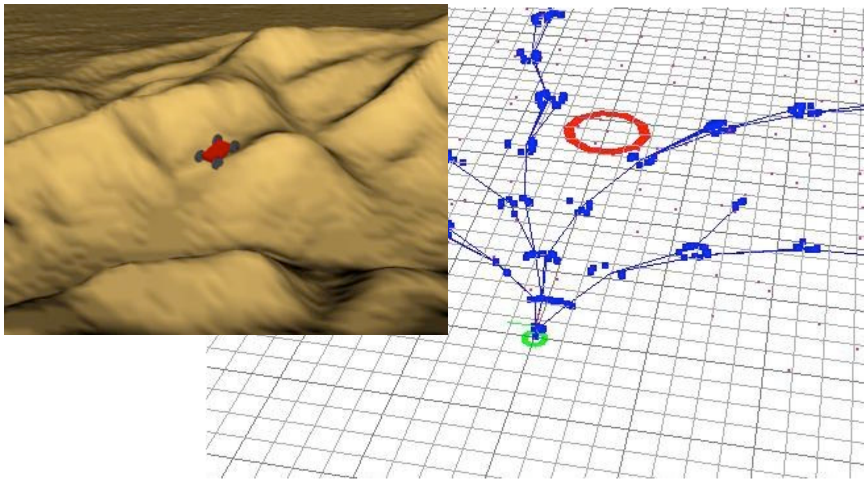
- **A summary of ongoing rover technology development**
  - Focus is on advancing Mars science exploration capability
  - Covers representative Mars Technology Program tasks
  - Including some that have matured to mission infusion
  - Strong emphasis on increasing navigational autonomy
  - Enhancing capability for reliable rough terrain mobility
  - Extending the range of uninterrupted science traverses
  - Enabling instrument placement in one command cycle
  - Developing software in a standard framework (CLARAty)
  - Introducing a higher "decision-level" of onboard autonomy
  - Prototyping novel system architectures e.g., multi-robotic
  - Not covered here are aerial mobility tasks (NRA LCMT)

Coverage—Task Area and PIs

- **Rough Terrain Traverse**
  - R. Simmons (CMU), A. Kelly (CMU), S. Dubowsky (MIT)
- **Long Range Navigation**
  - R. Li (OSU), A. Stentz (CMU)
- **Instrument Placement**
  - P. Backes (JPL), O. Khatib (Stanford)
- **Higher Level Autonomy**
  - T. Estlin (JPL)
- **Enhancements of MER**
  - A. Rankin-A. Stentz (JPL/CMU), W. Kim (JPL), S. Chien (JPL), P. Leger (JPL), P. Backes-O. Khatib (JPL/Stanford)
- **Multi-Robot Operations**
  - T. Huntsberger (JPL)—two tasks

Rough Terrain Traverse

Rover Navigation for Very Rough Terrain



Objectives:

- Develop algorithms for rover navigation over rough terrain
- Reason autonomously about vehicle dynamics rover-terrain interaction in the face of uncertainty
- Search in high-dimension cost-risk space using efficient stochastic planning methods
- Integrate with CLARAty and validate in a relevant environment

PI: **Reid Simmons**
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Co-I: **David Wettergreen**
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Participating Organizations: Carnegie Mellon

Facilities: Carnegie Mellon (FRC), JPL (CLARAty)

URL: http://www.frc.ri.cmu.edu/projects/roughnav

Funding Profile ($K):

Year 1	Year 2	Year 3
190	199	208

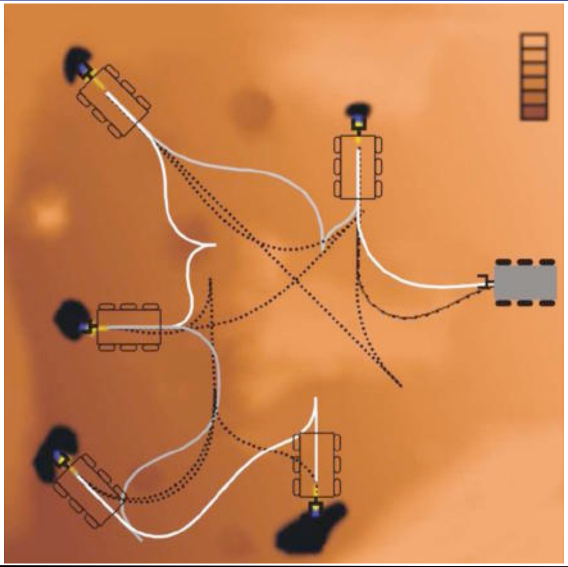
Milestones:

FY05: Refine heuristically-guided search; evaluate in simulation and prepare rover motion terrain characterization models

FY06: Refine the navigation algorithms; validate motion planning with rover during desert field experiment

FY07: Develop motion models specific to Mars rover prototype; integrate fully with CLARAty; benchmark performance against existing algorithms; validate integration cooperatively with JPL

Very Rough Terrain Motion Planning for Rovers



Objectives:

- More complete planning algorithm.
- Highly generic solution.
- More complex terrains.
- Improved understanding (in planning) of rover kinematics and dynamics.
- Improved computational efficiency based on a hierarchical approach.

Task Manager:
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Participating Organizations:
CMU, JPL

Facilities:
JPL Mars Yard, Rocky 7

Funding Profile ($K):

Year 1	Year 2	Year 3
283	276	280

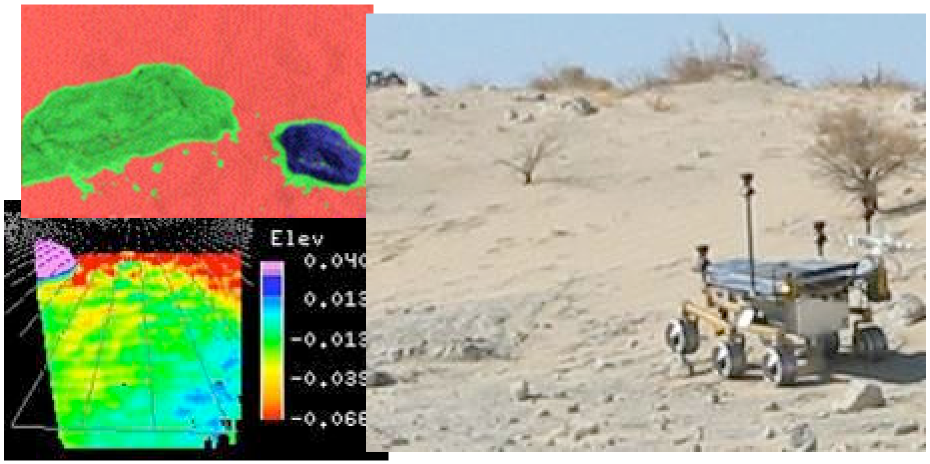
FY05-FY07 Milestones:

FY05 Rover vehicle dynamic model; 3D trajectory generator; Test environment; Visualization and simulation; CLARAty integration.

FY06 Seamless planning data structure; Sliding mechanisms; CLARAty integration.

FY07 Dynamic edge updates; Pose lattice Dstar; Generic API; CLARAty integration.

Multi-Sensor Terrain Classification and Terrain-Adaptive Navigation for Rovers in Very Rough Terrain



Objectives:

- Develop improved algorithms for navigation, trajectory planning, and hazard avoidance in challenging terrain
- Develop algorithms for robust multi-sensor terrain classification and traversability analysis
- Integrate predictions of terrain traversability with navigation work to yield a novel terrain-adaptive navigation method
- Experimentally validate all algorithms on MIT and JPL rover testbeds

PI: **Steven Dubowsky, MIT**
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Co-I: **Dan Helmick, JPL**
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Participating Organizations: MIT, JPL, Wash. U.

Facilities: MIT Field and Space Robotics Laboratory, JPL Mars Yard and ISIL

URL: http://robots.mit.edu

Funding Profile ($K):

Year 1	Year 2	Year 3
$402k	$405k	$413k

Milestones:

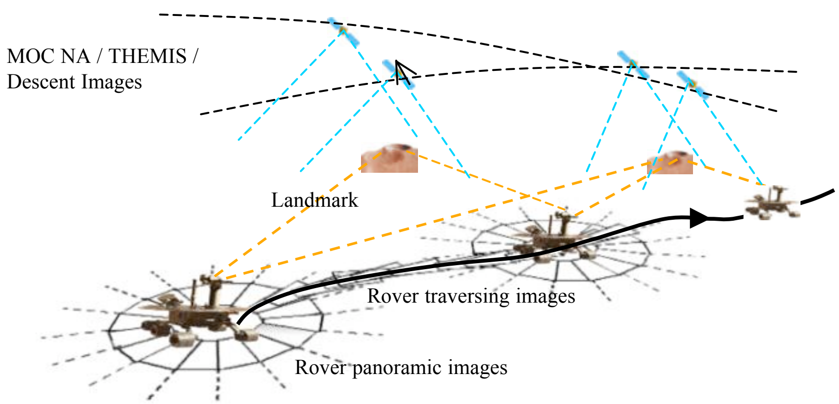
FY05 Demonstrate multi-sensor classification of two terrain types (MIT); Demonstrate improved hazard detection and stereo algorithms, traversability analysis and slip learning (JPL)

FY06 Integrate terrain classifier with multi-terrain slip prediction algorithm (MIT/JPL); Demonstrate slip-compensated path follower and high-fidelity traversability analysis integrated with path planner (JPL)

FY07 Demonstrate integrated multi-sensor terrain classification/ terrain-adaptive navigation on JPL rover (JPL/MIT)

Long Range Navigation

Long-Range Autonomous Rover Localization



Objectives:

- Develop an Incremental Bundle Adjustment (IBA) system for onboard rover localization
- Automate IBA by:
  - _ Improved tie point generation and selection
  - _ Integration of VO, ground and overhead imagery in Earth based and onboard systems
- Integrate the capability into CLARAty

PI: Ron Li
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Co-I: Andrew Howard and Larry Matthies (JPL)
K. Di (OSU)
Phone: (818) 393-6165 & (614) 292-4303
Collaborator: Ray Arvidson

Participating Organizations:
OSU and JPL

Facilities:
OSU, Mapping and GIS Laboratory
JPL, Machine Vision Group

Funding Profile ($K):

Year 1	Year 2	Year 3
$300K	$299K	$300K

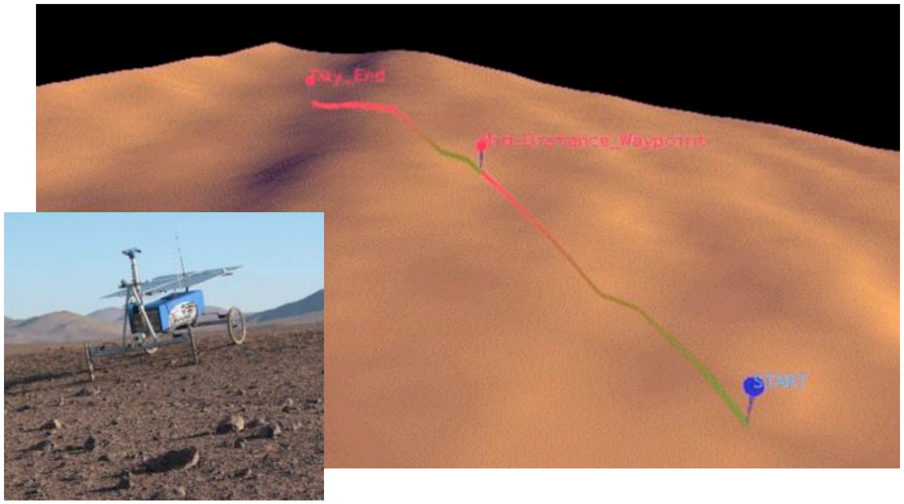
Milestones:

FY05 Algorithm and system design; Automatic tie point selection

FY06 IBA onboard and ground versions; Demonstration of the system in JPL and Silver Lake, CA

FY07 Improvement of IBA and Integration into CLARAty

Long-Range Rover Navigation



Objectives:

- **Increase distance of single-command rover traverse to kilometer range**
- **Improve traverse reliability and efficiency**
- **Conduct planetary analog demonstration to establish TRL-6**

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Participating Organizations: Carnegie Mellon, JPL

Facilities: Carnegie Mellon, JPL

URL: http://www.frc.ri.cmu.edu/projects/marsplan

Funding Profile ($K):

Year 1	Year 2	Year 3
299	304	297

Milestones:

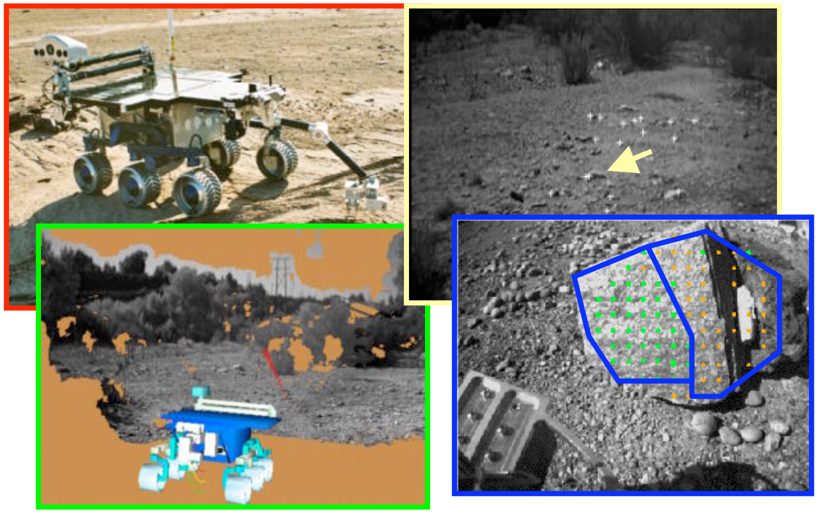
FY05: Refine algorithms for far-field obstacle detection and efficient continuous global path planning

FY06 Conduct experiments with continuous global path planning; implement multi-scale navigation software; achieve reliable one-command, one-kilometer traverse

FY07 Implement adaptive terrain evaluation software; attempt one-command two-kilometer traverse

Instrument Placement

Single Command Approach and Instrument Placement



Objectives:

- **Provide technologies needed for single command approach and instrument placement (SCAIP)**
  - **Long approach target prediction**
  - **Target handoff**
  - **Vision-guided manipulation**
  - **Automated target selection**
- **Utilize technologies in integrated demonstration from 10 meters**

Task Manager:

Paul Backes
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Participating Organizations:

JPL, ARC

Facilities:

JPL: Rocky8, Marsyard
ARC: K9, MarsScape

Funding Profile ($K):

Year 1	Year 2	Year 3
$388*	$423	-

*Includes ARC - Yr 1: $175K; Yr 2: $175K

Milestones:

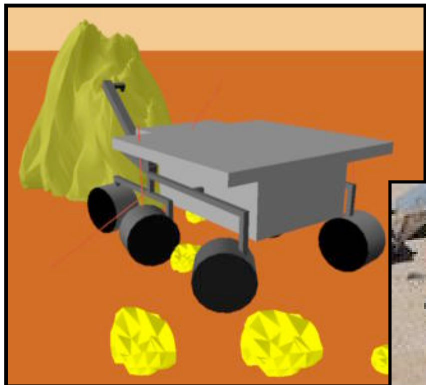
FY05 - Develop and test long approach target prediction and vision-guided manipulation algorithms (JPL)

- Develop and test terrain-based matching and automated target selection algorithms (ARC)

- SCAIP 3 m demonstration

FY06 - Integrated 10 m demonstration utilizing all SCAIP technologies

Whole Rover-Arm Coordination



Objectives:

- **Enable coring from a low-mass rover**
- **Model and simulate coring operations**
- **Extend arm workspace using rover degrees of freedom**
- **Coordinate rover and arm motion during contact tasks such as coring**

Task Manager:

Oussama Khatib, Stanford University
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Participating Organizations:

Stanford University, JPL

Facilities:

Stanford Robotics Laboratory,
JPL Marsyard,
JPL Manipulation Laboratory

Funding Profile ($K):

Year 1	Year 2	Year 3
$299	$291	295

FY05-FY07 Milestones:

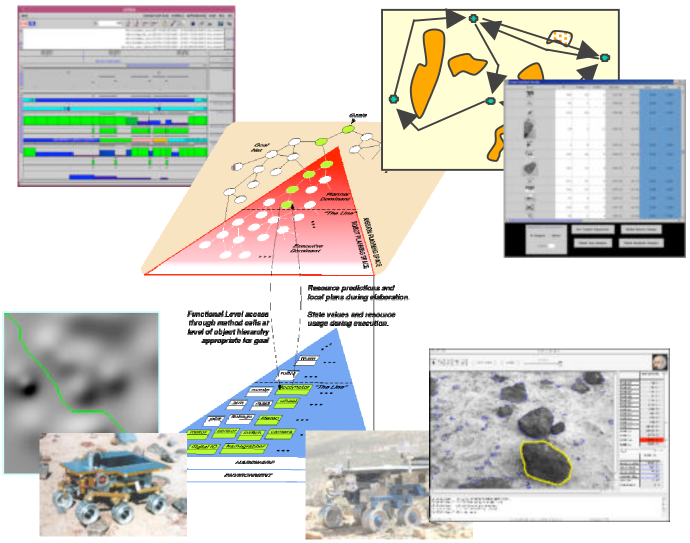
FY05 Baseline rover-tool sampling system design
Rover-tool coring simulation system

FY06 Empirical coring tests from a rover
Refined rover-tool models and simulation
Rover-arm reconfiguration control algorithms

FY07 Implement rover-arm reconfiguration control
Field test coring on 30 deg slopes on a low-mass rover

Higher Level Autonomy

Generic Decision Layer Framework



Objectives:

- Design and develop a generic Decision Layer software framework to easily support and deploy high-level, integrated rover autonomy technology
- Focus technology integration and testing on systems that will support future rover mission concepts (including long-range traverse, automated science targeting, opportunistic science, and automated fault handling)

Task Manager:

Tara A. Estlin (818) 393-5375
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Participating Organizations:

JPL, ARC

Facilities:

FIDO, Rocky 8, Rocky 7, CLARAty test bed, ROAMS, Maestro, JPL Mars Yard

Funding Profile ($K):

FY05	FY06
700	350

FY05-FY06 Milestones:

FY05 Develop generic DL infrastructure design

Integrate and demonstrate capabilities for onboard autonomous data analysis

FY06 Implement generic DL infrastructure

Integrate and demonstrate set of integrated DL capabilities within new framework

Enhancements of MER

Technology Infusion Strategy

- **Expose progress of technology development to project managers via demos, field testing, technology validation, reports.**
- **Develop NASA technology testbed infrastructure to provide a common platform for validation (field test, simulation testbed, models)--e.g., CLARAty**
- **For near-term missions (MRO, Phoenix, MSL):**
  - work with PIs and project CogEs to realign the tasks (scope, schedule, and resource) if the technology is applicable and infusion is still possible.
- **For longer term mission (2011 and beyond):**
  - maintain close communication with other focused technology programs and pre-projects so that they can leverage off the work developed under the base technology program (and note recent MER direct infusion case for Whole Rover-Arm Coordination…)
  - Work with PIs to realign the tasks to better address the future needs of the Mars Program

Prior R&D Infusion to MER

	Technology	Funding Source	Description	PI/Technologist
1	Long Range Science Rover	NASA (Code R and MTP)	Provides increased traverse range of rover operations, improved traverse acuracy, landerless and distributed ground operations with a large reduction in mass	Samad Hayati Richard Volpe
2	Science Activity Planner	NASA (Code R and MTP)	Provides downlink data visualization, science activity planning, merging of science plans from multiple scientists	Paul Backes Jeff Norris
3	FIDO: Field Integrated Design and Operations Rover	NASA (MTP)	Developed TRL 4-6 rover system designs, advancing NASA capabilities for Mars exploration; demonstrated this in full-scale terrestrial field trials, Integrated/operated miniaturized science payloads of mission interest, coupling terrestrial field trials to	Paul Schenker Eric Baumgartner
4	Manipulator Collision Prevention Software	NASA (MTP)	Computationally efficient algorithm for predicting and preventing collisions between manipulator and rover/terrain.	Eric Baumgartner Chris Leger
5	Descent Image Motion Estimation System (DIMES)	NASA (Code R and MTP)	Software and hardware system for measuring horizontal velocity during descent, Algorithm combines image feature correlation with gyroscope attitude and radar altitude measurements.	Andrew Johnson Yang Cheng et al.
6	Parallel Telemetry Processor (PTeP)	NASA (Code R and MTP)	Data cataloging system from PTeP is used in the MER mission to catalog database files for the Science Activity Planner science operations tool	Mark Powell Paul Backes
7	Visual Odometry	NASA (MTP)	Onboard rover motion estimation by feature tracking with stereo imagery, enables rover motion estimation with error < 2% of distance traveled	Larry Matthies Yang Cheng
8	Rover Localization and Mapping	NASA (MTP)	An image network is formed by finding correspondences within and between stereo image pairs, then bundle adjustment (a geometrical optimization technique) is used to determine camera and landmark positions, resulting in localization accuracy good for trav	Ron Li Clark Olson et. al.
9	Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT)	NASA (Code R and MTP)	Performs traversability analysis on 3-D range data to predict vehicle safety at all nearby locations; robust to partial sensor data and imprecise position estimation. Configurable for avoiding obstacle during long traverse or for driving toward rocks for	Mark Maimone
10	Lithium-Ion Batteries	NASA (Code R and MTP), Air Force (AFRL)	Significant mass and volume savings (3-4 X) compared to the SOA Ni-Cd and Ni-H2 batteries.	Richard Ewell Rao Surampudi

New MER Technologies
(FSW Release 9.2)

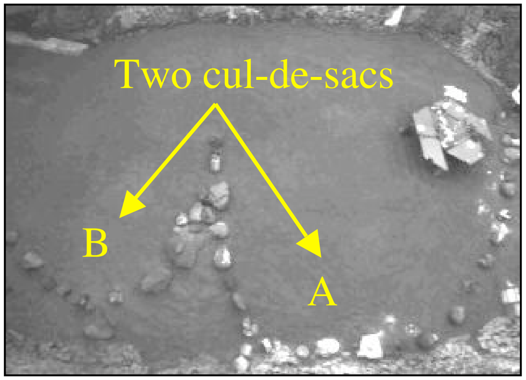
D* Integration into MER (Arturo Rankin, JPL 347 w/ CMU)
https://tdaweb.jpl.nasa.gov/otis/print.cfm?id=2735&docId=1778

Visual Tracking Integration into MER (Won Kim, JPL 347)
https://tdaweb.jpl.nasa.gov/otis/print.cfm?id=2468&docId=1248

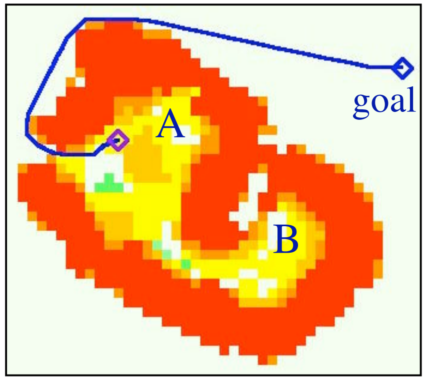
Onboard Science for Mars Exploration Rovers (Steve Chien, JPL 317)
https://tdaweb.jpl.nasa.gov/tda/view.cfm?id=2778&docId=1827

IDD Auto Deploy and Terrain Collision Checking (Chris Leger, JPL 347)
Stand-alone documentation provided (MER direct funding)

D* Integration into MER



Testing on JPL MER SSTB



D* cost map

D* assisted hazard avoidance

Task Mgr: Arturo Rankin
Phone: (818) 354-9269
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Co-TM: Mark Maimone
Phone: (818) 354-0592
Email: mwm@robotics.jpl.nasa.gov

Participating Organizations: JPL, Carnegie Mellon University

Facilities: MER SSTB in ISIL sandbox, MER Avionics Simulator, ROAMS

Objectives:

- Configure CMU Field D* for MER (less memory required, faster computation time)
- Integrate Field D* algorithm into MERFSW
- Command D* to evaluate the cost of traveling from each Gestalt arc endpoint to the goal
- Replace goal seeking arc votes with D* arc votes in the arbiter
- Perform Gestalt local hazard avoidance and D* global planning simultaneously

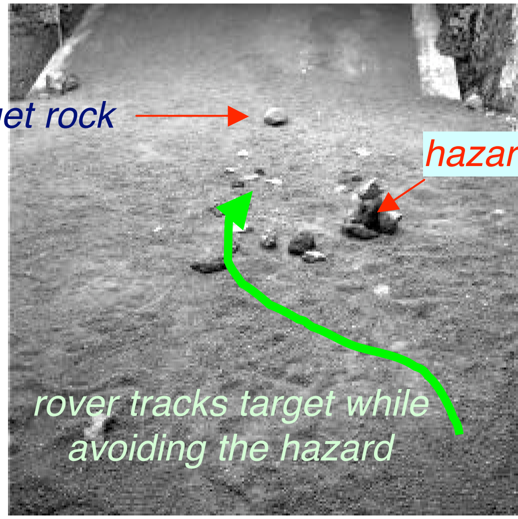
Milestones:

- Complete regression testing on the MER SSTB by mid Apr 2006
- MERFSW 9.2 upload to Mars early June 2006
- Checkout on Mars during 5 sols (TBD)

Mission Impact:

- Smarter negotiation of extended obstacles
- Less hazard avoidance failures on cluttered terrain
- Longer autonomous traverses per sol by MER rovers and during future missions to Mars

Visual Target Tracking Infusion into MER



target at 6 m away

target at 2 m away

Objectives:

- Develop and test the visual target tracking (VTT) flight software to be ready to upload
- Enable flight demonstrations of accurate target approach on Martian surface using MER navcam stereo cameras.
  - IMU 5-10% error (50-100 cm over 10 m)
  - VO 1-2% error (10-20 cm over 10m)
  - VTT 0.1-0.5% error (1-5 cm over 10 m)

PI: **Won S. Kim**
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Participating Organizations:

JPL

Facilities:

- MER SSTB (Surface System test bed) facility
- MER SSTB rover

Milestones:

FY05: Complete VTT FSW implementation and unit testing

FY06: Perform VTT regression tests, document, and conduct VTT operational checkout experiments in June on Mars

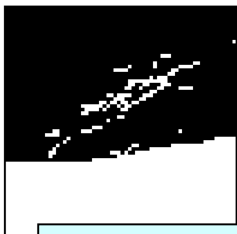
Mission Impact:

VTT increases science return by enabling accurate target approach, a key element to reduce 3-sol MER baseline to a single sol for instrument placement from 10 m away.

Onboard Science for MER

Dust Devils Results
- Detection in red

Original



Extracted Clouds

Objectives:

- Develop algorithms onboard detection of atmospheric science events
  - Clouds
  - Dust Devils (DD)
- Flight validate above technologies
- Assess overall benefits and end to end costs

PI: **Steve Chien**
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Participating Organizations:

ASU (Greeley), Texas A&M U. (Lemmon)

Facilities: None

URL: http://ai.jpl.nasa.gov/

Milestones:

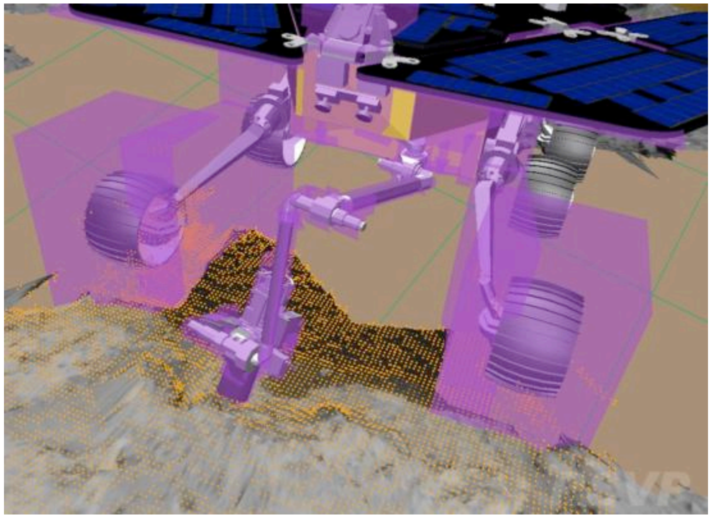
FY05: Develop and validate cloud and DD detection algorithms meeting science requirements; unit testing

FY06: regression testing for R9.2 FSW build, upload and operations

Mission Impact:

> 2x improvement in science return of cloud and DD science campaigns (…measured as events captured per fixed downlink)

IDD Autonomous Instrument Placement



Objectives:

- Enable MER mission rover final target approach and IDD (arm) instrument placement within a single uplink command sequence from 2-10 meters
- Implement flight software for automated arm path planning to a target and collision prediction between arm, rover, and terrain after a rover motion
- Enable “recon” arm placements (autonomous sampling of multiple targets) and “mid-traverse” arm placements without additional uplink cycles to increase data return and provide initial target assessment before in-depth investigation

PI: Chris Leger
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Participating Organizations: JPL

Facilities: MER Surface System Testbed, ISIL (Building 317 sandbox)

URL: http://marsrovers.jpl.nasa.gov

Milestones:

FY05 - Developed autonomous instrument placement software for MER and deployed in MER flight software environment

FY06 - Regression testing of software build for uplink in June

- Operational checkout on Spirit and Opportunity planned for July/August.

FY07 - Begin MSL inheritance of autonomous instrument placement software from MER in September

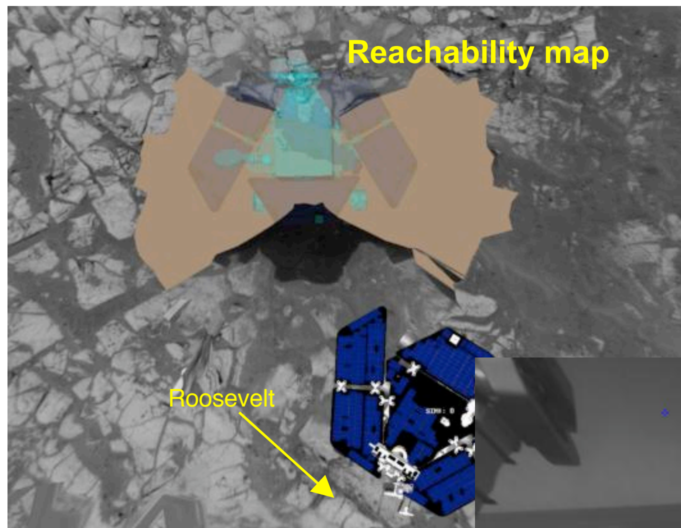
Mission Impact:

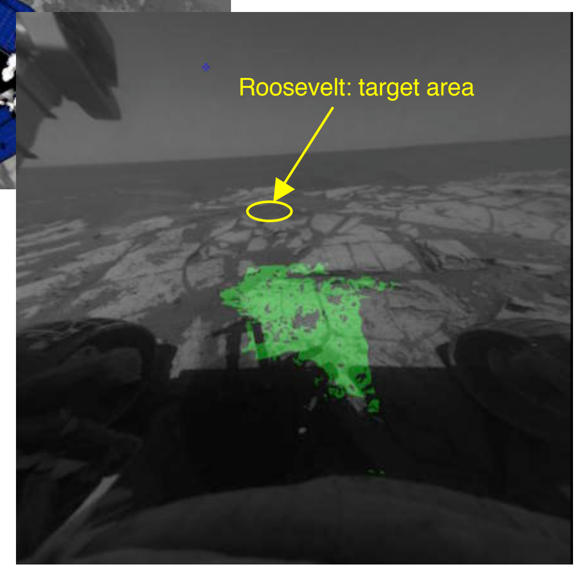
Reduces number of command cycles for instrument placements and enables new operational scenarios for autonomous survey/recon of potential science targets

Significant Event (Rover-Whole Arm Coordination: O. Khatib/Stanford, P. Backes/JPL)

- **MER rover base placement was developed under this task through the Mars Technology Program NRA and the subject technology was recently used on MER in a first operational test to accommodate the Opportunity rover IDD shoulder azimuth joint degradation.**

- **Rover-Base Placement is integrated into MER flight ground operations environment**
  - **Computes rover location and heading that will place the IDD target in the IDD work-space minimizing use of azimuth joint for desired target**
  - Uses knowledge of the terrain to compute rover attitude via calls to RSVP
- **Used to compute Opportunity rover location and heading for the approach to feature Roosevelt on sol 724/725**
- **IDD campaign on sols 726 thru 730 completed successfully***





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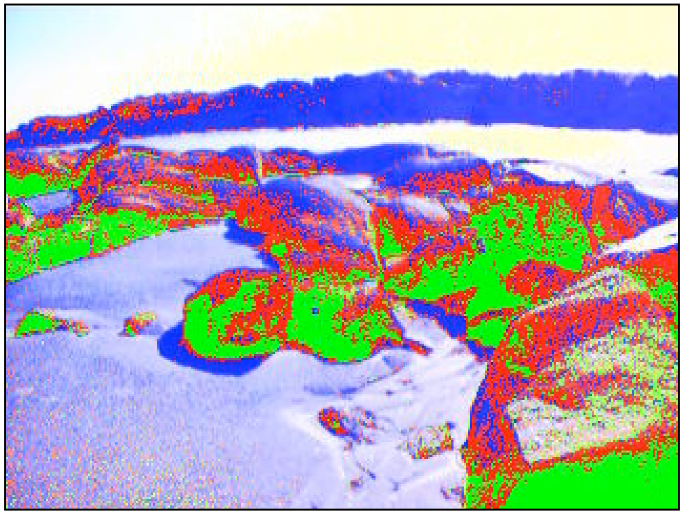
* **Refer to MER-B Uplink/Downlink Report Area for details of activities from sols 724 through 730**

Significant Event (Multi-Sensor Terrain Classification: S. Dubowsky/MIT, L. Matthies/JPL)

- **Demonstrated a unified approach to multi-sensor terrain classification**
  - Color, texture, range-based classification from visual data
  - Vibration-based classification from wheel-terrain interaction data
  - Developed two different methods for classification
    - Mixture of Gaussians and Support Vector Machine
  - Developed two different types of multi-classifier fusion
    - Bayesian fusion and Meta-Classifier fusion
- **Result: Enables autonomous classification of MER-like terrain as sand, rock, or mixed with average accuracy of 85%**
- **This is a technology innovation**
  - No previous on-board terrain classification capability
  - **New functional capabilities**
    - **Detecting/avoiding sandy slopes**
    - **Improved traversability prediction**
    - **Integral part of slip prediction (JPL)**

Local classification of terrain from wheel-terrain interaction vibration signature



Classification of distant terrain from visual features (blue is sand, green is beach grass, red is rock)

Multi-Robot Operations

Robotic Systems for Access to Steep Terrain

Objectives

- Develop and demonstrate an integrated suite of onboard adaptive hardware/software algorithms that autonomously enables mobile robots to *safely* move about highly sloped environments (≥20º) and explore potentially important science sites that are considered *hard-to-reach*.
- Develop and demonstrate a formal mathematical game-theory basis for rover pose reconfiguration, adaptive driving strategies, and management of onboard resources (batteries, actuators, etc).

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Participating Organizations: JPL, MIT, CMU

Facilities: Planetary Robotics Lab (JPL Bldg 82-108), Robotic Assembly & Science Integration Lab (JPL Bldg 82- 106), MarsYard (JPL), Arroyo Seco; MIT Field and Space Robotics Lab; CMU Field Robotics Center

URL: http://prl.jpl.nasa.gov

Funding Profile ($K)

FY00	FY01	FY02	FY03	FY04
380	300	250	250	250

Milestones:

FY'00: Design, develop, and demonstrate rover sensor-based control & geometric adaptation to changing terrain for improved mobility at lower risk.

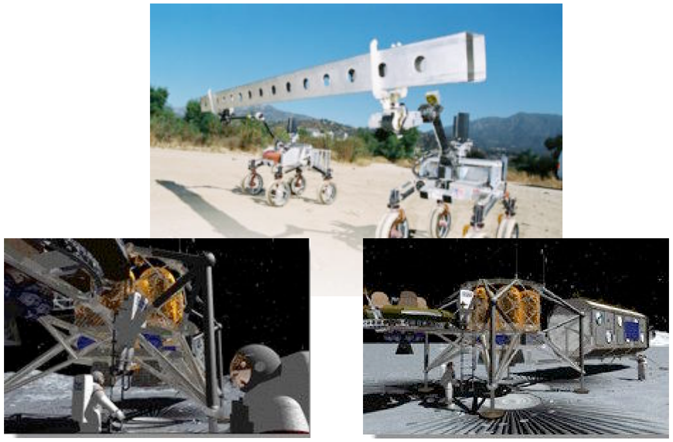
FY'01: Develop a distributed mobility system for the *cooperative traverse of a cliff-side wall*--up to 75º grade-- where a rover traverses a cliff-face assisted by two semi-mobile railed robotic anchoring stations.

FY'02: Develop and demonstrate a distributed sensing/mobility system for mapping, traverse and science data acquisition on a cliff-side wall.

FY'03: Demonstrate a continuous movement traverse with onboard fusion of reactive/predictive pose reconfiguration strategies over steep terrain.

FY'04: Demonstrate a continuous movement traverse with adaptive driving strategies over rough, steep terrain.

Robotic Construction Crew



Objectives

- Develop an integrated hardware/software system for autonomous and telerobotically assisted construction operations of modular habitats and infrastructure on lunar and planetary surfaces.
- Demonstrate the integrated system in a terrestrial analog environment using an ensemble of robotic platforms for construction of a base level habitat structure.

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Co-I: Maja Mataric
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Email: mataric@usc.edu

Participating Organizations: JPL, USC

Facilities: Planetary Robotics Lab (JPL Bldg 82-108), Robotic Assembly & Science Integration Lab (JPL Bldg 82- 106), MarsYard (JPL), Arroyo Seco; USC Interaction Lab

URL: http://prl.jpl.nasa.gov

Funding Profile ($K)

FY00	FY01	FY02	FY05
670	370	250	200

Milestones:

FY'00: Develop and demonstrate a sensor-based control architecture for multiple robots performing coordinated transport of a rigid extended object over outdoor irregular terrain.

FY'01: Develop and demonstrate a multi-robot system capable of not only transporting, but also cooperatively accessing-manipulating-lifting large, extended objects.

FY'02: Develop and demonstrate a multi-robot system carrying out multiple aspects of autonomous robotic infrastructure support operations.

FY'05: Develop and demonstrate a control structure) for autonomous construction operations(i.e. base and wall deployment of a habitat structure). Test of concepts for seamless man and machine wireless interfaces.

Scaleable Rough and Steep Terrain Mobility for Lunar Exploration (ESMD/“ATHLETE”, B. Wilcox)

Summary and Conclusions

Related Work

- **Within MTP:**
  - *MSL Focused Technology (to date)*
    - Rover Navigation Validation; Instrument Placement Validation; SA/SPaH/Crusher/CAT/Manipulation
  - *MTP Base (NRA) work on Low Cost Mission Technologies)*
    - Mars Superpressure Balloons; Mars Montgolfiere Balloons; Mars Advanced Technology Airplane; other

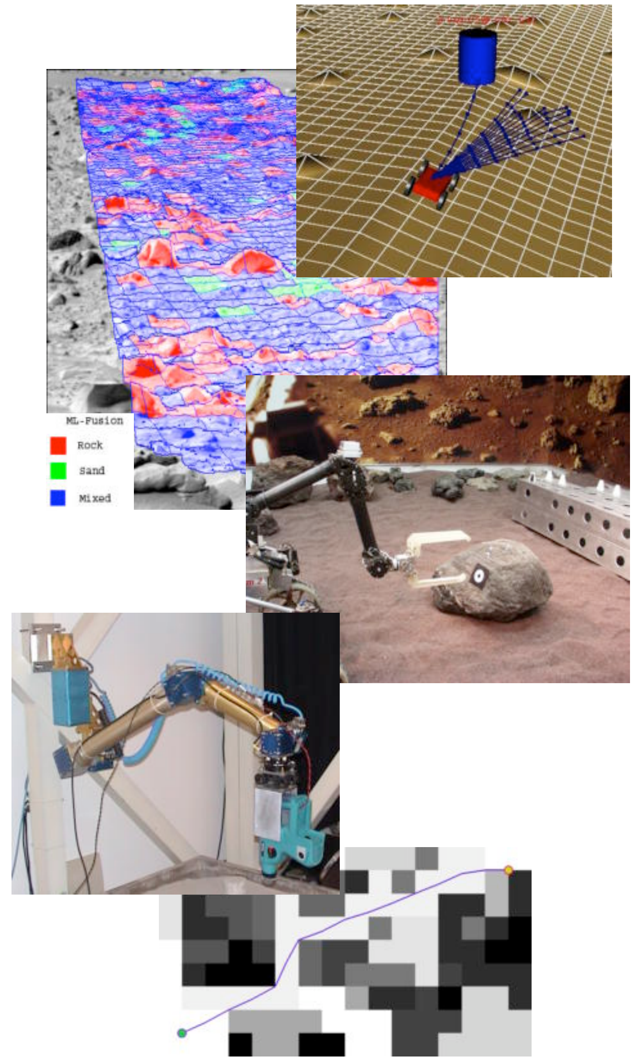
- **Others:**
  - *R&TD Mobility (to date)*
    - STAR (Steep Terrain Access Robot); Mobility Avionics; Software for Distributed Avionics; SOOPS (Science Operations on Planetary Surfaces)
  - *CICT IS/ESMD Transition (ends FY'05+)*
    - Autonomous Robotic Manipulation Control
  - *ESMD Advanced Capabilities Division Technology Development (continuing tasks)*
    - Rough and Steep Terrain Lunar Surface Mobility—ATHLETE; Telepresence of Remote Supervision of Robots
  - *CICT IS and SS CETDP (2000-2002)*
    - SMART (All Terrain Explorer; Cliff-bot); Robotic Work Crew

Performance Metrics (TRL 6 by 2007)

Performance Metrics	Current Capability	Anticipated Capabilities
Traverse Position Accuracy	5-10 % distance traveled	1 % distance traveled
Sloped/Rough Terrain Traverse	Random Slew/Slip	Closed Loop Visual Servo (~5-10%)
Sols for Instrument Placement	3	1
Onboard Science Data Processing	Image Compression	Event Detection/ Classification
Navigational Intelligence	Local Area Path Planning	Global Information Fusion/Planning

Significant Accomplishments (FY05-end)

- **Fast dynamic path planning for rough terrain; modeling of rover-terrain interactions; fast regional planning with slip constraints; far field navigational planning**
- **Robust multi-sensor terrain classifier; color, texture, and range; also color and vibration fusion**
- **Integration of bundle adjustment (BA) and visual odometry (VO) for long range traverse**
- **CLARAty-based integration framework and execution system for “decision layer”**
- **Vision guided manipulation for fast, robust instrument placement; conceptual framework for coordinated rover-arm coring activities under force constraints**
- **Development, through CLARAty V&V path, of candidate technologies for MER infusion; Maestro-CLARAty-ROAMS “RoverWare”**
- **Comminution trade studies and breadboard implementation; coring testbed studies**



Backup

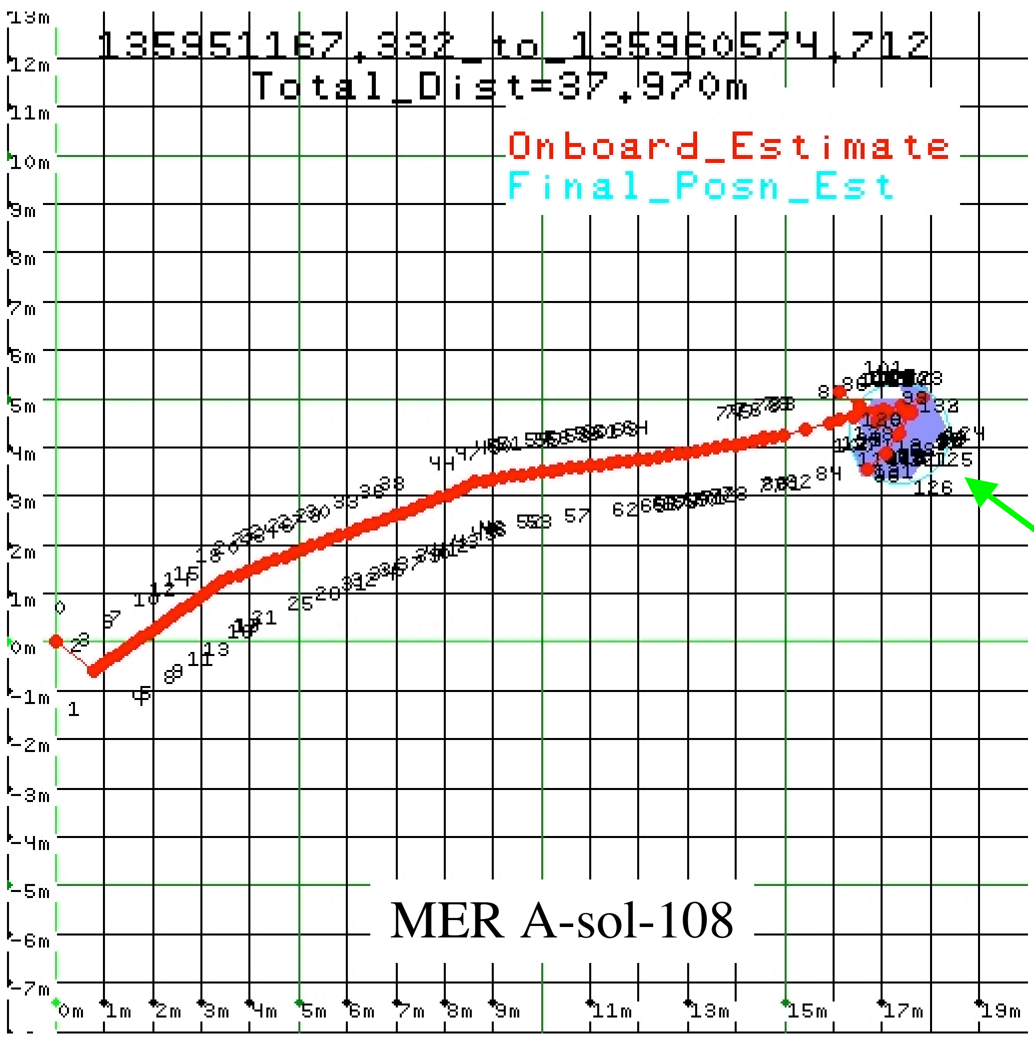
(MER Technology Infusion Tasks)

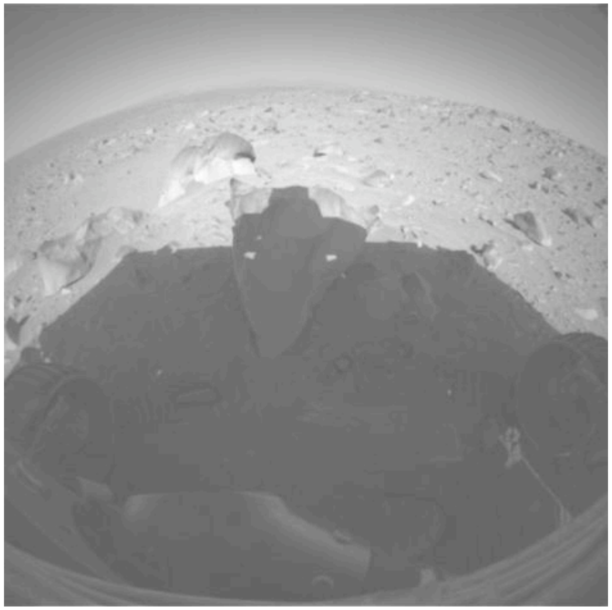
D* Integration into MER

- **What: D* assisted hazard avoidance**
  - Integrate CMU Field D* global path planning software into MERFSW
  - Simultaneously perform local hazard avoidance and global planning
- **Why: Enable rover autonomous navigation around extended obstacles**
  - During autonomous navigation, Spirit has become stuck several times when multiple rocks are nearby (e.g., A-sol-108, A-sol-144)
  - Autonomous navigation in cluttered environments with solely local hazard avoidance can require frequent user intervention, thus slowing mission progress

D* Integration into MER

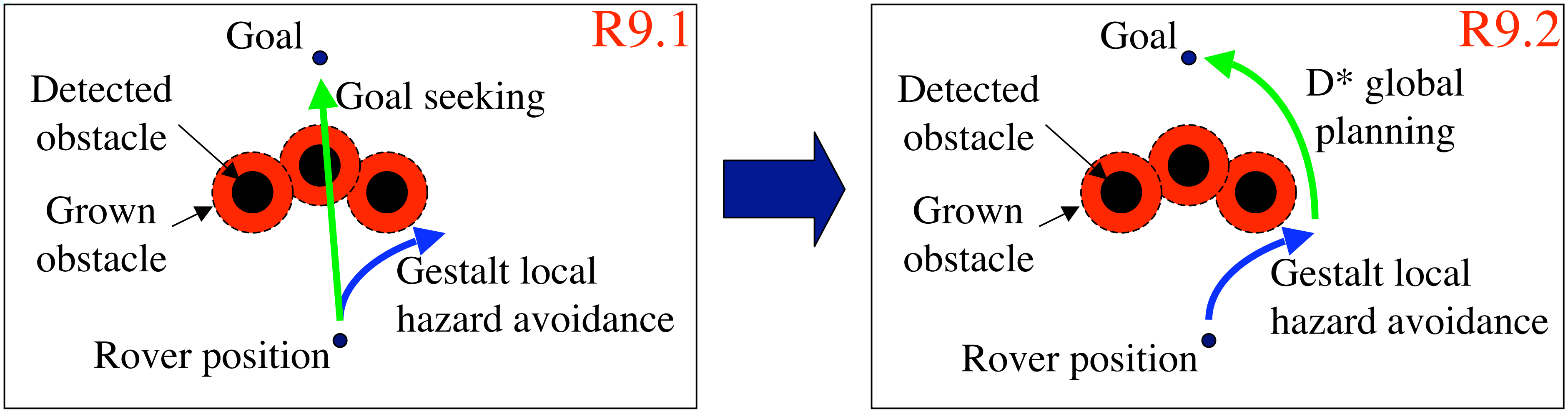
Example where rover gets stuck





During autonomous traverse, rover tried in vain for ~1 hour to get past a cluster of rocks

D* Integration into MER



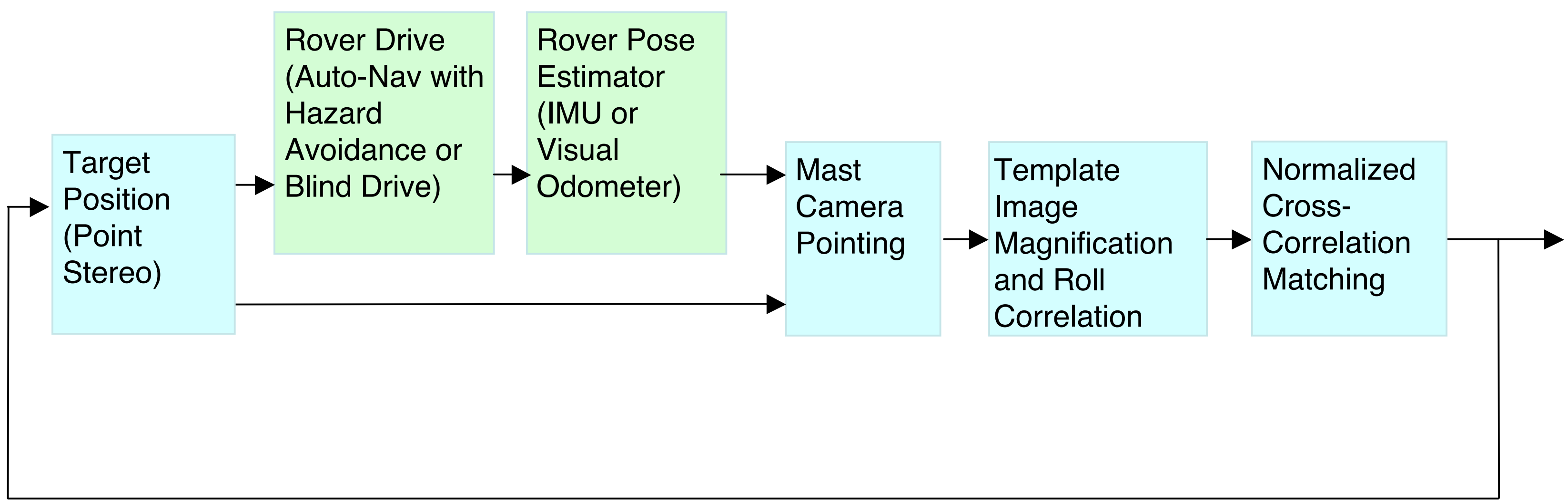
- **How: Replace goal seeking arc votes with D* arc votes**
  - Gestalt performs traversability analysis on a set of arcs out to ~3m
    - Each arc is assigned an “Obstacle” vote
  - D* evaluates the cost of traveling from the end of each arc to the current global goal position
    - Each arc is assigned a “D*” vote
    - D* arc votes replace MER R9.1 goal seeking arc votes
  - Obstacle and D* arc votes are merged

Visual Tracking Integration into MER

- **What: Develop and test the visual target tracking flight software to be ready to upload**
- **Why: Enable flight demonstrations of 10-m target tracking on Martian surface using MER navcam stereo cameras.**
  - a key element to reduce a 3-sol operation to a single-sol
- **Allows tracking experiments in different operational modes**
  - blind driving
  - auto-nav with hazard avoidance
  - enable or disable visual odometry
  - flat terrain, slopes, and rough terrain
- **Products**
  - Visual target tracking flight software ready-to-upload
  - Software Development Folder Document
  - Regression Test Procedure

VTT Functional Diagram

- **How: Illustrates how visual target tracking (VTT) works**
  - Rover drive and rover pose estimator capabilities already exist in MER FSW



Onboard Science for MER

- **What**: **Flight demonstration of onboard science processing to:**
  - Mature technology for future missions
  - Learn about operations integration and flow (including science ops)
  - Document improved science return from onboard processing

Onboard Science—Background

- **MER performs significant science campaigns to catch transient events: *Dust Devils* and *Clouds***
- **Why: Onboard detection and tracking of these events can dramatically improve science per fixed downlink**
  - E.g, 8-to-25% of cloud campaign images actually have clouds (source- Mark Lemmon)
  - Can increase temporal resolution with summary products

Dust Devil Tracking—Process

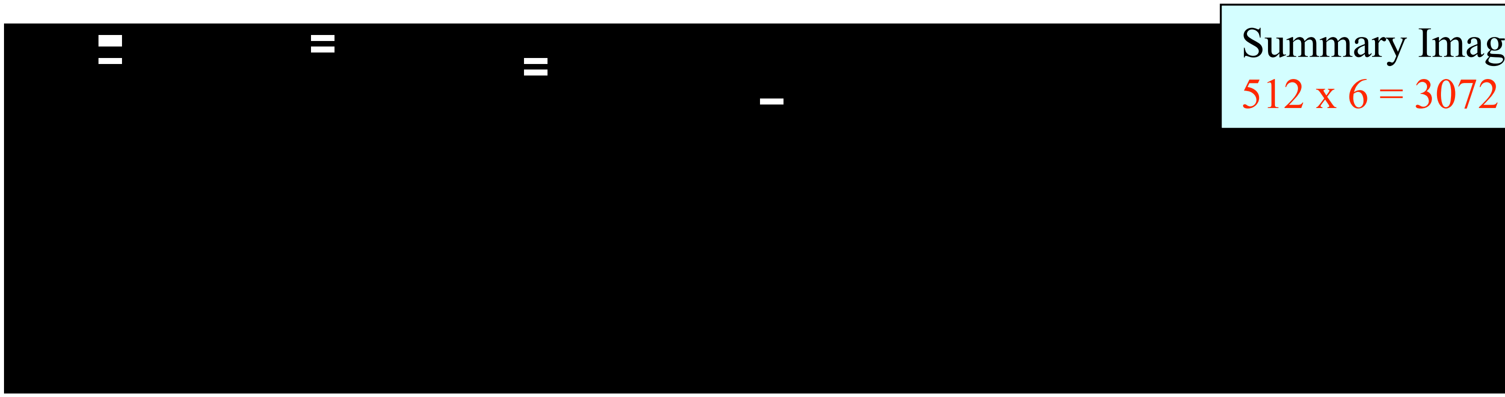
How:

- Low pass filtering (median)
- Image reduction
- Intensity remapping
- Average Image (all-at-once) or trailing average (batch mode)
- Obtain difference between image and its average
- Separate motion from noise in diff image using edge detector weighted by the local noise
- Locate dust devils as blobs in the result
- Create data product using the dust devils found
- Add a buffer zone to the blobs
- Determine rectangular regions from blobs

Dust Devil Tracking

Basic product
- Red boxes show detections

Summary Image
512 x 6 = 3072 bytes



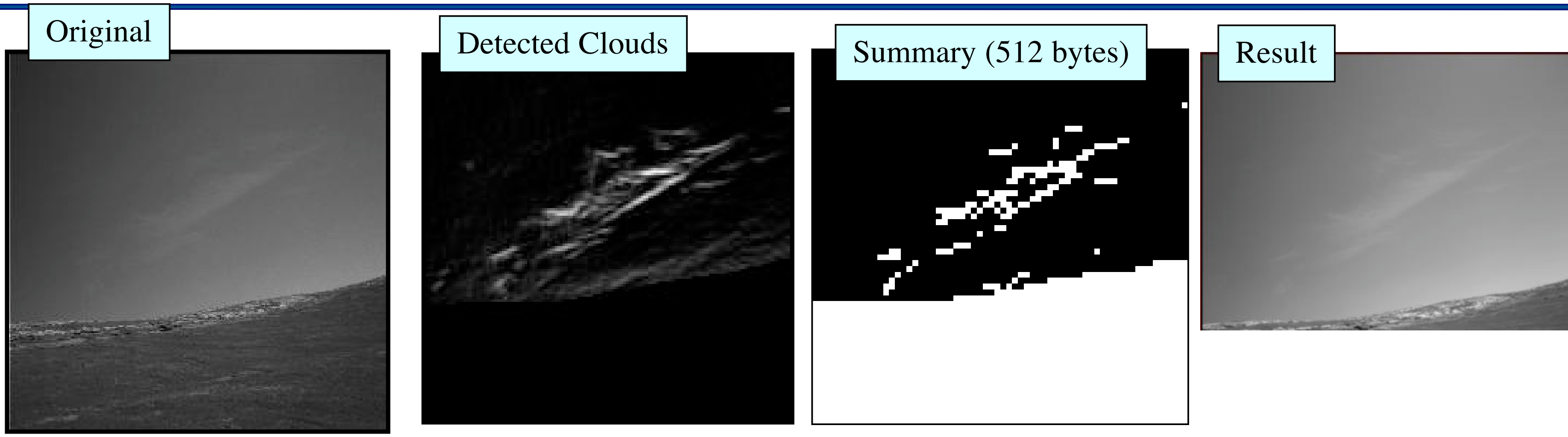
Science-only product

Cloud Detection—Process

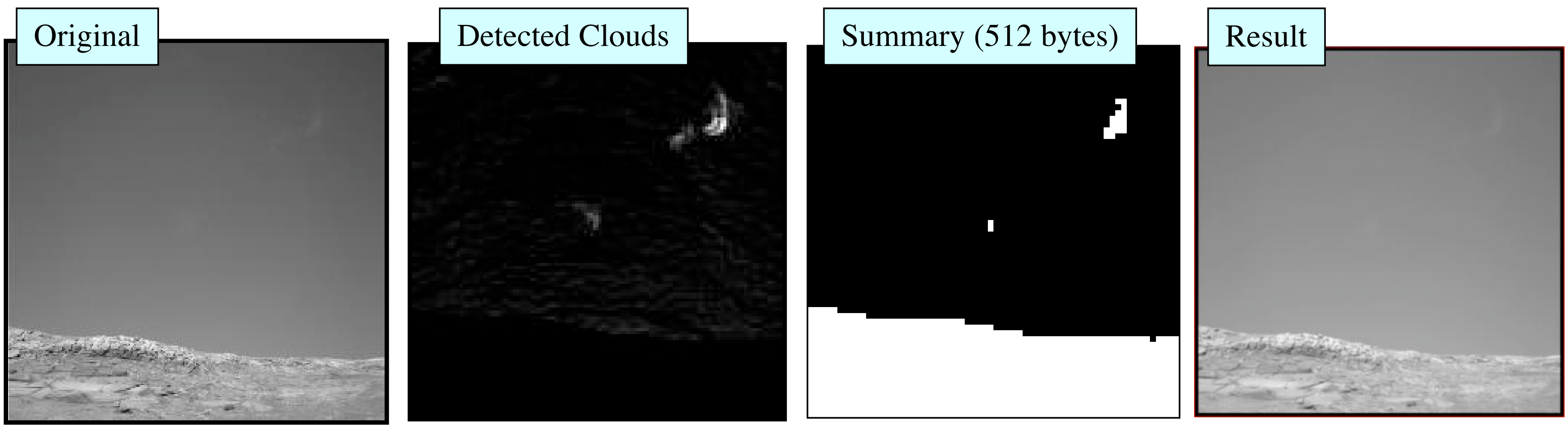
How:

- **Low pass filtering (median)**
- **Image reduction**
- **Intensity remapping**
- **Average image (for multiple images)**
- **Obtain sky mask by running sky detector**
  - Find sky seeds in homogenous regions
  - Growing algorithm using edge image
  - Add buffer zone to skyline
  - Determination of horizon line
- **Mask image (or average image) with sky mask**
- **Estimate edges, variance and noise of image (or average image)**
- **Detect clouds as variations in the edge image weighted by the noise**
- **Create data product using the variance image**
- **Bound rectangular region with horizon line**

Cloud Detection



Detection of evident cloud



Detection of wispy cloud

IDD Autonomous Instrument Placement

- **Goal: Enable final target approach and instrument placement within single command cycle**

- **Operational Components:**
  - Stereo-based terrain map generation
  - Free-space visibility analysis
  - IDD terrain collision checking
  - Target position sensing
  - Surface normal computation
  - Surface roughness analysis
  - Kinematics configuration selection
  - Trajectory generation
  - Ground Data System updates